EFFECT OF IN-SITU PULSE-HEATING OF TANTALUM ANODES ON THE RADIATION FROM BREMSSTRAHLUNG DIODES*

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Abstract

Pulse-heating tantalum anodes in bremsstrahlung diodes to > 2600 K results in improved bremsstrahlung production. Proton current (from hydrogen impurities) is reduced by more than two orders of magnitude, beam pinching is suppressed, and the far-field dose is increased by 20%. The dose increase is a result of reduced ion current and enhanced electron reflexing through the sub-range tantalum foil. A stretching mechanism was used to keep the foil flat and taut during heating. The radiation pattern is symmetric and hollow, producing a more uniform near-field dose distribution than for a pinched beam. This technique can be used to improve x-ray production on high-power generators such as Decade.

I. PULSE-HEATED TANTALUM

Tantalum (Ta) anodes, used as x-ray sources in high-power electron-beam diodes, can be copious sources of ions due to the fact that Ta easily absorbs gas, even at elevated temperatures (maximum absorption at 1300 K). These low-Z impurities (hydrogen, carbon, etc.) are released and ionized when the e-beam heats the tantalum foil, thus creating a space charge in the vicinity of the anode as well as an ion current that can be a substantial fraction of the diode current. Gases on the surface can be removed by moderate heating prior to a shot, but gases entrained in the interior of a Ta foil require higher temperatures (2300 K or greater) to be removed.

Initial tantalum heating experiments [1] on Gamble II (1.5 MV, 0.7 MA, 60 ns) used a capacitor bank and step-down transformer to resistively pulse-heat 50-ì m-thick foils to T > 2200 K, and demonstrated increased dose, reduced ion current and reduced pinching. To heat the 100-μm thick, lartge area Ta converter on Decade [2], a more energetic, longer-duration heating pulse is required.

A bank consisting of 24 automobile batteries was built to test the effects of heating for Decade parameters. The bank is switched on and off with solid-state switches. A one-second long heating pulse was chosen to allow many e-folding times for hydrogen to diffuse from the interior of the tantalum (e.g., 120 ms at 3000 K for 50 μm). Current and voltage waveforms, shown in Fig. 1, were measured on a 28×30 cm area foil, appropriate for Decade.

Also shown in Fig. 1 is the tantalum temperature, calculated using published temperature-dependent heat capacity (Cp), resistivity (η) and emissivity (ε) data. The temperature is calculated using the tantalum voltage measured between the battery bank connections, V_{Ta}. If conduction loss is negligible compared with radiation loss, the heating equation becomes:

$$mC_p \frac{dT}{dt} = \frac{V_{Ta}^2}{R} - \varepsilon A \sigma \left(T^4 - T_0^4\right) . \qquad (1)$$

Here, m is the tantalum mass, R is the resistance, A is the radiating area, σ is the Stephan-Boltzmann constant and T_0 is the initial (room) temperature. The temperature, T, determines the resistance which, with the voltage, determines a calculated current. This calculated current is in good agreement with the measured current, verifying the accuracy of the calculated temperature.

Several minutes prior to a shot, one such heating cycle is used to clean the tantalum *in situ*. This heating cycle allows entrained gases to diffuse out from the interior. The heating cycle is repeated immediately before a shot to further clean the tantalum and keep the surface hot enough to prevent further adsorption. The generator is

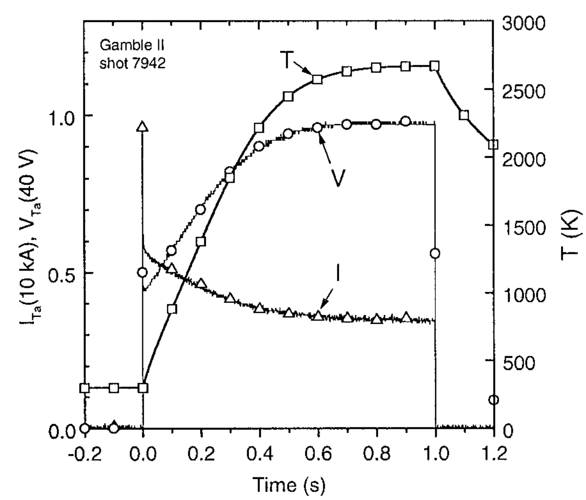

Figure 1. Measured voltage (circles) and current (triangles) for heating a 100 μm × 28 cm × 30 cm tantalum foil. The calculated temperature (squares) exceeds 2600 K.

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14. ABSTRACT

Pulse-heating tantalum anodes in bremsstrahlung diodes to > 2600 K results in improved bremsstrahlung production. Proton current (from hydrogen impurities) is reduced by more than two orders of magnitude, beam pinching is suppressed, and the far-field dose is increased by 20%. The dose increase is a result of reduced ion current and enhanced electron reflexing through the subrange tantalum foil. A stretching mechanism was used to keep the foil flat and taut during heating. The radiation pattern is symmetric and hollow, producing a more uniform near-field dose distribution than for a pinched beam. This technique can be used to improve x-ray production on high-power generators such as Decade.

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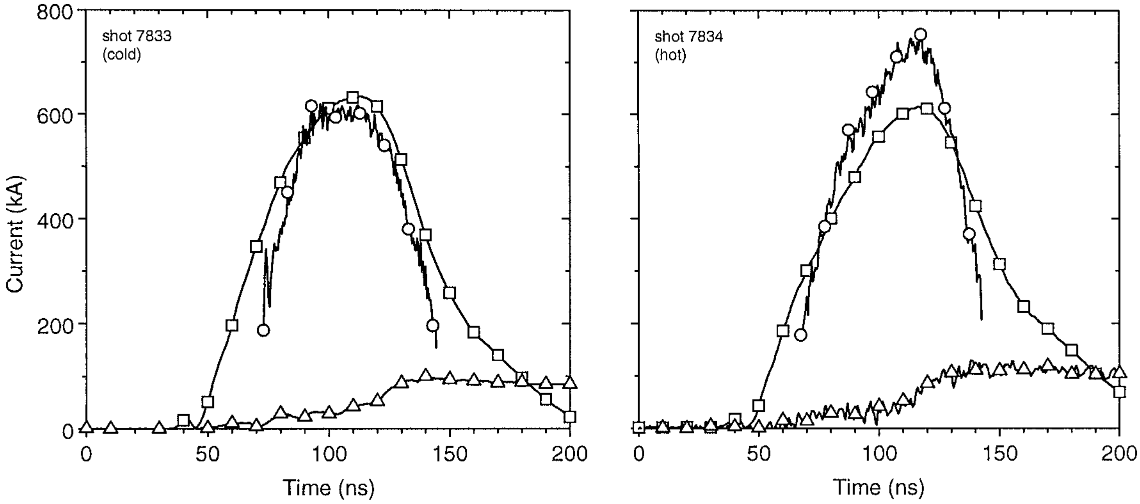

Figure 2. Comparison of current waveforms for cold (left) and hot (right) anodes. Measured total current (squares), ion current (triangles), and electron current inferred from filtered x-ray measurements (circles).

fired 200 ms after the end of the second heating pulse, when the temperature is 2100 K.

II. GAMBLE II EXPERIMENTS

A second experiment on Gamble II used the same configuration as in Ref. [1], but with 100-µm-thick Ta and the battery-bank heating circuit. New diagnostics for this experiment included nuclear activation of carbon placed inside the center conductor to detect energetic protons and a differentially-filtered PIN diode array [3] to determine the electron endpoint voltage and the effective electron current. Both diagnostics yielded new information about the effects of heating.

The proton component of the beam was measured with the ^{12}C(p,ã)^{13}N nuclear reaction on graphite samples located upstream of the hollow cathode. With cold anodes, the carbon samples were ablated unless a stainless steel plate with an array of small holes (1.5% transparency) attenuated the proton beam. With hot anodes, the activity detected using the attenuating plate was at the background level. With the plate removed, statistically significant counts were obtained, indicating a 450× reduction in the number of protons relative to cold anodes.

An array of five PIN diodes with different filters was used to determine the electron current and voltage based on Cyltran [4] modeling for a gaussian distribution of electron-incidence-angles on the tantalum. Typical results for cold and hot anodes are compared in Fig. 2. For the cold anode, the inferred electron current is less than the measured total current by an amount consistent with the measured ion current. For the hot anode, the inferred electron current is significantly greater (750 kA vs. 600 kA) than the total current, while the ion current is similar

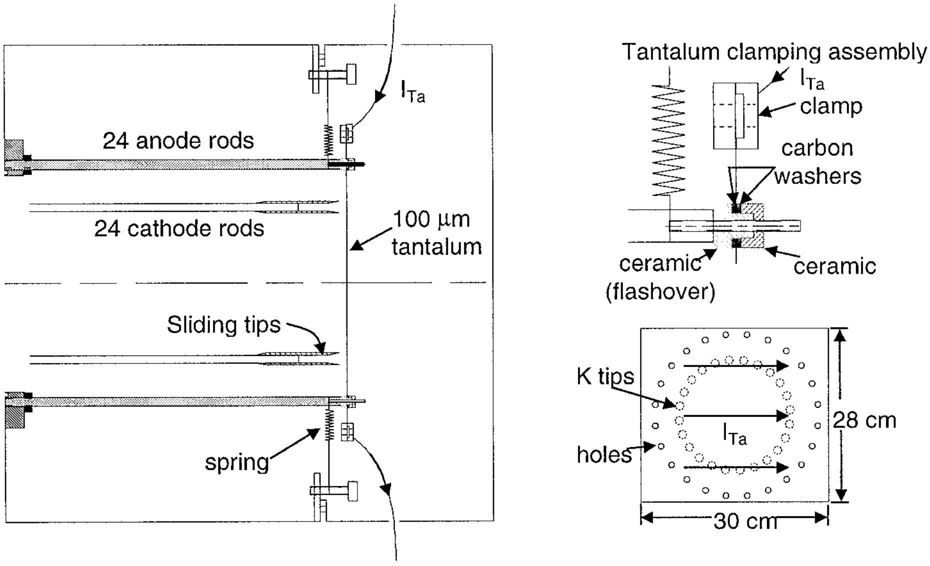

Figure 3. Sketch of tantalum stretching mechanism: top view cross section (left), close up of clamping assembly (upper right) and view of tantalum foil from front (lower right).

to the cold anode case. The overestimated electron current could be a consequence of electron reflexing, where transmitted electrons are reflected back to the tantalum by a virtual cathode. For cold anodes, the presence of ion space charge can prevent virtual cathode formation.

Pinhole camera images of the bremsstrahlung emission from the tantalum indicated less pinching for hot anodes than for cold anodes. However, the patterns for hot anodes were also filamentary and asymmetric. This could be the result of wrinkling when the heated foil expands, so a mechanism to stretch the tantalum while being heated (appropriate for Decade) was developed and tested during the third Gamble II experiment.

A sketch of the stretching mechanism is shown in Fig 3. The diode is a coaxial arrangement of anode and cathode rods. The Ta anode is clamped between ceramic isolators and attached to the ends of the 24 anode rods. The ends of the rods are pulled radially outward with strong springs to tension the tantalum. The heating circuit is connected to the tantalum with brass clamps that connect along the length of the shorter (28 cm) sides of the Ta foil. An important feature that makes this system work is the use of carbon washers between the ceramic pieces. Without these washers, the heating current is concentrated at the edges of the holes in the tantalum, increasing the temperature there and either limiting the central temperature to a lower value than desired or melting the foil. The carbon washers provide a conducting path with an appropriate resistance to avoid this problem.

The springs are stretched about 10 mm to allow the tantalum to expand during heating (2% linear expansion at 3000 K). After a heating cycle, the tantalum is flat and smooth inside the circle formed by the anode rods, and wrinkled outside the rods because of the brass clamps. During a shot, the ceramic surfaces flash over to complete the circuit to the tantalum.

The rod cathode depicted in Fig. 3 is similar to one investigated during the development of Decade modules [2]. This cathode produces reproducible centering of the beam on the anode. The sliding cathode tips and the multi-rod construction of the center conductor were developed at the Decade facility at the Arnold Engineering Development Center, Tullahoma, TN.

The time-integrated pinhole photographs in Fig. 4 illustrate the drastic differences between cold and hot anodes. The cold anode undergoes a rapid pinch with the emission concentrated on-axis. With hot anodes, pinching is reduced resulting in a hollow circular pattern. Electron emission from the individual cathode tips results in a set of circles at the cathode diameter, indicating the beam dwells at this large radius much longer than it does with a cold anode. Each of the 24 cathode rods produces a local pinch at the inner edge of the cathode which then propagates inward. The velocity of propagation is determined by the time required to form anode plasmas to offset the electron space charge, presumably a significantly longer time for the hot anode than for the cold anode.

The dose distribution in the near field will be more uniform for the hot anode case than for the cold anode case, which resembles a point source. The annular emission of the hot anode resembles that of a ring diode. An array of four such diodes on Decade would then produce a more uniform exposure than four cold anodes.

The dose in the far field was measured two different ways: CaF_2 thermoluminescent dosimeters (TLDs) record the time-integrated dose at 1 m from the tantalum, and scintillator-photodiode (PD) detectors measure time dependent x-ray signals. The PD signals for different shots are integrated to measure relative dose in the scintillator. Comparable data using the stretching mechanism were obtained for three shots with cold anodes and four shots with hot anodes. This set of shots used the same anode-cathode gap setting (9 mm) and had almost identical electrical power waveforms (0.5 TW peak, 60 ns FWHM) and total energy (30 kJ). The maximum current and voltage values were 0.4-0.5 MA and 1.0-1.2 MV. Both the TLDs and integrated PDs indicated a 20% increase in dose for the hot anode case,

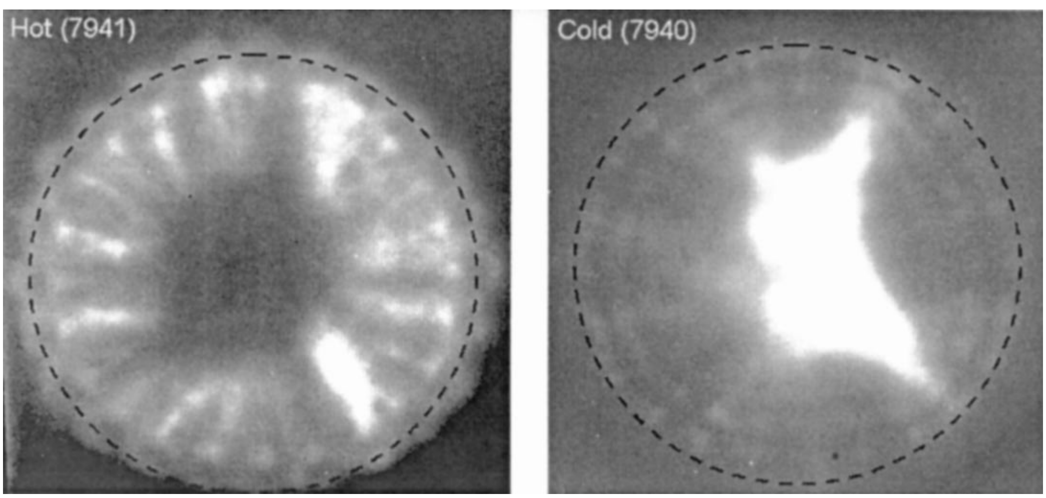

Figure 4. Time-integrated x-ray pinhole photographs of tantalum anodes heated (left) and non-heated (right) cases. The dashed circle indicates the cathode location (see Fig. 3, lower right).

averaged over the two sets of shots. This result is similar to the dose increase observed in the previous two Gamble II experiments without the stretching mechanism.

The x-ray distribution from the tantalum was measured with four PDs collimated to detect the radiation inside circles with r = 2, 5, 8 and 13 cm. The signals were time-integrated, normalized to the total integrated signal for a cold anode shot and are plotted versus radius in Fig. 5. The only cold anode shot (7938) with collimated PD data was the one with the largest dose of the three cold shots, based on TLDs and an independent PD measurement. About 50% of the x-ray emission is inside r = 5 cm, and more than 30% is inside r = 2 cm. The three shots with hot anodes have radial distributions that are very different from the cold shot. With hot anodes, emission inside r = 2 cm is negligible, and the emission from the entire tantalum area (r = 13 cm) is 22% larger, on average. This quantitative source distribution is consistent with the qualitative pinhole photographs in Fig. 4 and the TLD measurements.

III. CONCLUSIONS AND APPLICATIONS

Pulse-heating of tantalum anodes to temperatures near melt has several beneficial effects for bremsstrahlung production from high-power e-beam diodes. The proton component of the beam is reduced by orders of magnitude (450× on Gamble II). Beam pinching is reduced, resulting in a hollow radiation source that will produce a more uniform dose distribution in the near field compared with an intense pinch (point source). The dose is about 20% larger with heated anodes, a result of reduced ion current and enhanced electron reflexing by a virtual cathode mechanism. A foil stretching mechanism keeps the tantalum taut during heating, greatly improving the symmetry of the source compared with shots without active stretching.

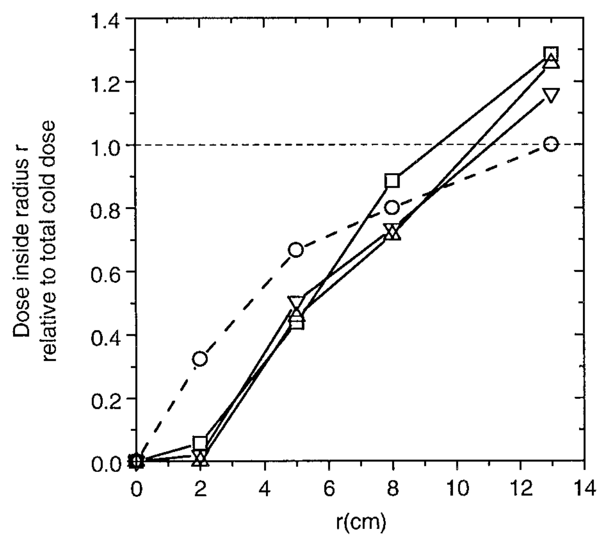

Figure 5. Dose distributions measured with collimated PD detectors relative to the total dose for a cold anode (circles). The cathode tips are located at r = 8 cm, and the anode rods are at r = 13 cm. Shots with hot anodes are indicated by squares and triangles.

A particular application for this technique is the Decade generator. On Decade, a plasma opening switch (POS) is used to generate a fast (50 ns), high voltage (1-2 MV) pulse.[2] Pinch-beam diodes are the only demonstrated technique to efficiently produce bremsstrahlung from this generator. Alternate diodes that would produce more uniform dose distributions, such as ring diodes, require vacuum convolutes on the downstream side of the POS that probably will result in power flow losses. Using the heated tantalum anode in this environment would increase the dose and make the dose distribution more uniform in the near field.

A brief experiment (6 shots) was performed on a Decade module (DM2) at Titan Pulse Sciences, San Leandro, CA, to test the feasibility of the hot tantalum system in the Decade environment. Preliminary results from this experiment indicate increased dose (30%) but reduced pinching was not observed, possibly due to POS plasma reaching the diode.

Other applications for this technique include reflexing converters to improve the efficiency of warm (10-100 keV) x-ray generation and e-beam diodes with small anode-cathode gaps to increase the current density without premature gap closure from electrode plasma expansion.

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